Experimental and Analytical Study on the Force-carrying Process of the Sand-collecting Shovel

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Abstract: The sand-collecting shovel is an important part of the track sand removing vehicle. In order to analyze the force changes during the sand collecting process, and get an optimization method of its structure, the paper took the method of the combination of experiment and numerical simulation. The sand test bench was designed and built to simulate the sand-collecting working process. Because the torque reflected the force of the shovel during the sand-collecting working process, the torque received by the sand collecting shovel was measured. Using the method of coupling discrete element and multi-body dynamics method, the force of the straight blade, 15 degree the 30 degree blade under the same working conditions were simulated and analyzed in the X, Y and Z directions. The experimental result was similar to the simulation results, which proved the feasibility of the coupling method of discrete element and multi-body dynamics to research the interaction mechanism between the sand and shovel. Then, the force of shovels working in the depth of 50mm and 70mm were simulated and the values were compared. It can be seen that changing the edge angle caused a different force regular changing of the blade in three directions, but the total force of the sand collection was reduced. The research results provided a theoretical basis for the structural optimization of the sand shovel and have an important guiding significance for relevant mechanical design.
***Keywords*:** sand shovel, sand, discrete element method, three-dimensional forces, force analysis, torque

1. Introduction

The development of railway track sand removal vehicles is of great significance for ensuring the normal development of railway transportation in desert areas. The research team designed a small track sand removal vehicle for the special needs of a transportation company in Inner Mongolia Autonomous Region, China. As an important mechanical-sand interaction component, the sand-collecting shovel is a key component of the sand removal vehicle. During the working process, the sand-collecting shovel divided and collected the sand piles accumulated on the track through its own rotating motion. After using for a while, the edge of the sand-collecting shovel produced a large deformation, which was extremely unfavorable for the normal use of the sand removal vehicle. According to the preliminary analysis, this may be caused by an excessive impact force of the sand shovel when dividing the sand. In order to carry out a way for the structural optimization of the shovel, it is necessary to study and analyze the stress state of the sand-collecting shovel during the process of collecting sand.

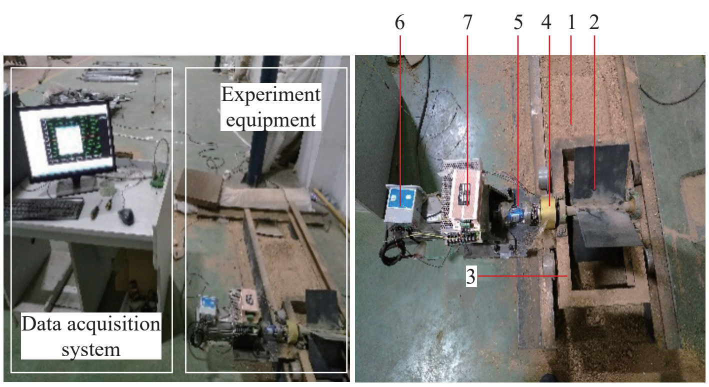
Studying the force behavior of sand shovel is a category of sand-mechanical interaction research. Due to the discontinuity of sand media, studying the interaction between sand media and mechanical structure has always been an important research content of agricultural machinery and mining machinery [1; 2; 3]. In order to solve the problem caused by sand material discontinuity in numerical simulation, many improved finite element numerical calculation methods (FEM) have been developed, such as Smooth Particle Hydrodynamics (SPH), no unit (Element Free Galerkin, EFG), Reproducing Kernel Particle Method (RKPM), Material Point Method (MPM), Meshless Local Petrov–Galerkin (MLPG), etc.[4; 5; 6], but these numerical calculation methods have many shortcomings compared to the Discrete Element Method (DEM). Most of them need to integrate according to the grid or other conditional background, and the calculation was still inaccurate. DEM can be used to study the interaction process between mechanical structure and sand [7; 8]. The force of mechanical structure can be calculated and the contact process of sand and mechanical structure can be observed microscopically. A large number of studies have shown that it is feasible to use the discrete element method to study the interaction mechanism between sand and mechanical structures [2; 9; 10; 11; 12; 13].Thus, the method of DEM was taken and the force of their interaction was researched.

A considerable amount of research indicated that improving the mechanical structure, such as trencher, planter and bulldozer won a good result. Research on related structures was always limited by some factors. And some factors existed still restricted the accurate study of the interaction mechanism between sand and mechanical components. For example, different particle size distribution, water content or porosities, always showed great discrepancies [10; 14; 15]. Or some related calculations and simulations that took a long calculation time or the reliability of the calculation results was poor when compared with the experiment. The reason caused this phenomenon may be that the discrete element method only considered the mechanical between sand particles, the mechanical between mechanical structures was ignored. In order to get a more accurate analysis results, the force between the particles and the force between machinery parts should be calculated. So, the multi-body dynamics and discrete element method were combined to simulate the force of the sand shovel. The data interface uses the compiled software interface EA-Link, the software taken in the simulation were EDEM 2018 and ADAMS 2013. By calculating the two-ways exchange of the calculated result data, a more accurate calculation results can be obtained, which has a better research effect on the analysis of the force of the sand shovel [16; 17]. For the sand shovel blades, changing the edge angle was an simple but effective way to reduce the force of the sand shovel blades [18; 19]. What`s more, changing the edge angle of the blade actually changed the working area in contact with the sand. The structural shape of some farming equipment indicates that the change of the edge shape of the cultivating knife had a significant improvement on the force and soil discharge of the agricultural implement during the cultivation process [20]. However, the mechanism of force reduction has not been well explained. Therefore, it was proposed to analyze the three-dimensional forces of the blade and explore the micro-stress state of the blade during the sand-collection process.

2. Sand collection test

2.1 Construction of the sand shovel test bench

In order to verify the correctness of the simulation model, an experiment was carried out firstly. The structure of the test bench is shown in Figure 1. Main structures of the test bench include a sand storage tank 1, which has a size of 600 mm (length) × 200 mm (width) × 60 mm (deep). A sand shovel model 2, in the experimental process, the sand collecting depth can be changed according to the actual scale model, the sand collecting depth was 55 mm in the experiment. The single blade size of the sand collecting shovel was 200 mm (length) × 160 mm (width), fixedly mounted on the bracket 3. The sand collecting shovel was driven to rotate by the driving motor 6, the sand collecting shovel and the motor were connected by the flange of the torque sensor 5. The slip ring 4 was placed on the collecting shovel shaft to transmit the dynamic torque signal from the collecting shovel to the signal acquisition system which was attached in a computer. At the same time, the sand shovel was moved at a given speed in the direction of the frame 3 which simulated the movement of the sand removing vehicle on the track.



1. Sand bin and guide rail 2. Sand shovel 3. Frame 4. Slip ring 5. Torque sensor 6.Motor (0.4KW) and governor 7. Amplifier

Figure 1. Sand shovel test bench model

2.2 Collection of the torque signal from sand shovel

During the process of cutting and moving the sand shovel along the sand frame 3, a resistance generated in the sand shovel, so a resistance torque will be generated on the sand collecting shovel component. Then, the dynamic stress on the sand shovel blade will cause a response on the full-bridge strain gauge in the torque sensor, meanwhile, dynamic strain generated, and a varying voltage signal was generated and outputted by the external excitation voltage. Through the 4-channel slip ring wiring, the voltage excitation signal was respectively transmitted to the torque sensor, and the torque signal was transmitted to the amplifier. Finally, the voltage signal was transmitted to the computer through the signal acquisition device, thus, the signal collection, analysis and processing were completed. The chart of signal acquisition process was shown in Figure 2.

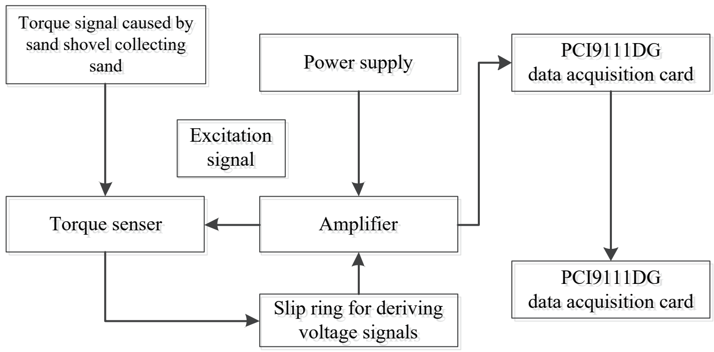


Figure 2. Data acquisition schematic

2.3 Test conditions

The material used for collecting sand shovel was ASTM 1045. There were two kinds of edge shape of sand shovel blade in the experiment. One shape was shown in the Figure 3. The edge angle of the blade was defined as α, also was the variable factors intended to be changed to test the cutting force of the sand shovel. Two blade edge angles of the sand shovel were designed, 0 ° (also straight blade) and 30 ° blade(α=30 degree) were designed. Radius of gyration for the sand shovel was D=0.4m, and the working width of the blade was L=0.2m. During the test, the translation speed of the sand shovel was 0.333 m/s, the rotating speed was 64 rpm, and the sand collection depth was 55 mm.

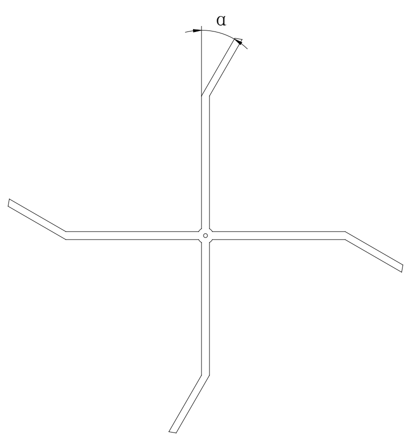


Figure 3. The shape angle α of the blade edge

2.4 Comparative analysis of experiment and simulation torque

The simulation showed that when the speed of the sand shovel was 64rpm and the sand collection depth was 55mm, the dynamic change of the torque of the two shapes of the sand shovel in a complete sand collecting cycle was shown in Figure 4. The blades of the sand shovel were rotated about 30 degrees to start dividing the sand and colliding with the sand. The torque was increased from 0 to 6.4 N.m. As the sand shovel continues with rotation, the second blade started to contact the sand. After a while, the sand collected by the last blade began to detach and was gradually thrown out, so the torque of the blade gradually decreased, but not to 0; with the rotation of the sand shovel, and after the second blade interacted with the sand, The torque received by the sand shovel again peaked. Each blade was sanded one time in one cycle, so four torque peaks in one cycle of the sand shovel can be seen apparently.

By simulating and analyzing the two shapes of shovel under the same working conditions, it was found that changing the shape of the shovel can reduce the peak value of the torque of the sand shovel. The average improvement effect in one cycle was theoretically 23.5%. The effect of reducing the impact resistance was very obvious.

In order to further verify the correctness of the simulation calculation, the test bench was used to measure the torque received during the sand collecting process, and the torque and fluctuation of the straight and 30° sand-collecting shovels under the simulation and test conditions were compared. It can be seen that under the same conditions, four force peak values of the sand-collecting shovels can be seen apparently. From the simulation conditions, the maximum fluctuation error between peak and peak was 19.2%. The large peak error between the experiment and the simulation may be caused by friction between the mechanical components driven on the test bench. From the comparison between simulation and experiment, the experiment had a good agreement with the simulation.

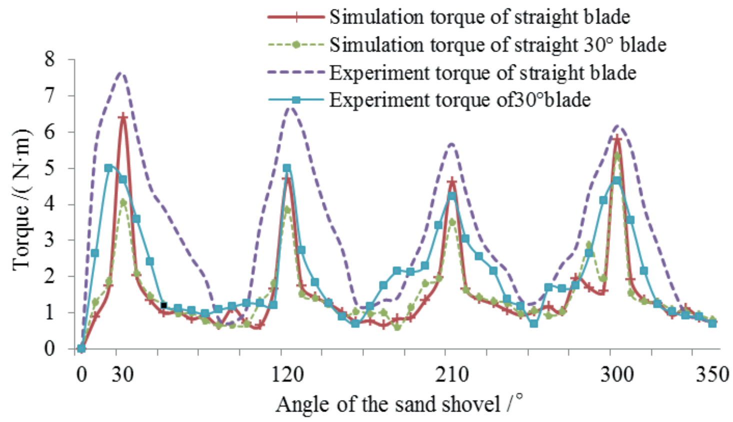


Figure 4. Torque at different angles during sand shovels working

It can be seen from Figure 4 that the torque obtained by the experiment was basically consistent with the simulated torque value, which proved that the data obtained by the discrete element simulation was effective for studying the interaction mechanism between the sand shovel and the sand. Then, a research on the force of the sand shovel with different edge shape and the analysis of the mechanism of the force changing was carried out.

3. Numerical simulation calculation

3.1 Selection of material parameters

The study of the force on sand particles was essentially an elasticity-plasticit analysis of the contact mechanics of granular solids under quasi-static conditions. During the interaction between the sand shovel and the sand particles, the sand particles were mainly affected by the force from the two aspects, namely their own gravity and the received external force, including between the sand particles and the sand particles or between the particles. Normal collision contact force $F_{n,ij}$, normal damping force $F_{n,ij}^{d}$, tangential collision force $F_{\tau,ij}$, tangential damping force $F_{\tau,ij}^{d}$. According to Newton's second law, the total force equation and the rotational equation of particle i are

$$\begin{cases} m_i \dfrac{dv_i}{dt} = m_i g + \sum\limits_{j=1}^{n_i} \left(F_{n,ij} + F_{n,ij}^{d} + F_{\tau,ij} + F_{coh,ij} \right) \\ I_i \dfrac{d\omega_i}{dt} = \sum\limits_{j=1}^{n_i} \left(T_{\tau,ij} + T_{r,ij} \right) \end{cases} \tag{1}$$

$$F_{coh,ij} = k_{coh,ij} A_{coh,ij} \tag{2}$$

Where:

I_i——Moment of inertia of particle i, unit: $kg \cdot m^2$

n_i——Total number of particles in contact with particle I, unit: PCS

vi——Movement speed of particle i, unit: m/s

ω_i——Particle i angular velocity unit: rad/s

$T_{\tau, ij}$——Tangential force moment of particle i, unit: N·m

$T_{r, ij}$——Rolling moment received by particle i, unit: N·m

$F_{coh,ij}$——Normal binding force of particles, unit: N

$K_{coh,ij}$——Particle surface adhesion energy density, unit: J/m^2

$A_{coh,ij}$——Particle contact area, unit: m^2

The adhesion energy density of the particles needs to be set according to whether the sand particles have cohesive force.

Since the experimental study was carried out in the desert area, which has a good fluidity and the texture was dry, Therefore, the Hertz-Mindlin (no-slip) model was used as the contact model for calculating the interaction between sand-sand and sand-sand shovel. By consulting the literature and using the stacking angle experiment, as shown in Figure 5, the basic parameters used in the simulation in Table 1 and Table 2 were obtained:

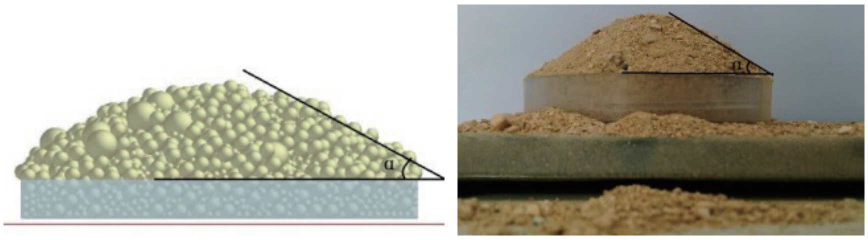


Figure 5. Stacking angle simulation and experimental results(α=31°±1°)

Table 1. Parameters of sand shovel materials(steel)

material	Poisson's ratio	Bulk density /(Kg/m^3)	Shear modulus /Pa
steel	0.3	7800	7e10
sand	0.25	2700	1e8

Table 2. Parameters Of material interactions

Material Interactions	Static friction coefficient	Rolling friction coefficient	Restitution coefficient
steel—sand	0.45	0.01	0.05
sand—sand	0.2	0.05	0.05

3.2 Modeling

A sand-collecting shovel model was established in the 3D modeling software, and the sand shovel model was about one tenth of the actual size, since the main objective of the study was the influence caused by the blade angle on the force variation, changing the size of the model will not cause too great influence on the law. Sand model was built in the EDEM software and in order to avoid the influence of sand trap shape on the interaction between the sand shovel and the sand, the geometry of the soil trough was larger than the working range of the sand shovel, and the effective geometry of the sand trough is 600mm(L) × 200 mm (width) × 60 mm (deep), the number of particles was about 130 000.

In order to explore the effect that changing the edge angle of the sand shovel on the force and test the applicability of the discrete element method in the research process, three types of shovel shapes, namely straight, 15° and 30° edge inclination were simulated. The sand collecting force simulation study was carried out under the condition of the sand collecting depth of 55 mm, and the models were shown in Figure 6 and Figure 7, meanwhile, the sand particles ratio was set according to the Table 3.

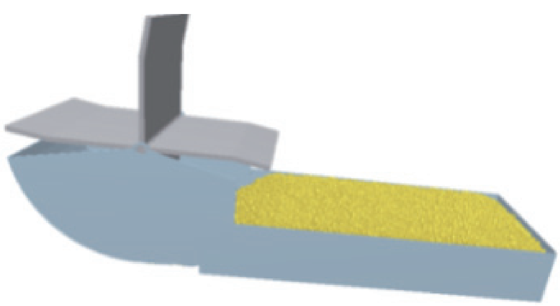


Figure 6. The shape of sand shovel model

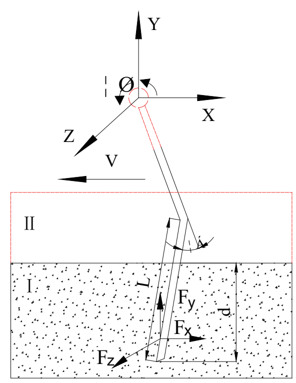


Figure 7. Schematic diagram of sand shovel stress analysis

Table 3. Proportion of particle size distribution of different particle sizes

Parameters	Value		
Diameter of sand partica D/mm	0.8	1.0	1.2
Quality ratio /%	10	80	10

4. Simulation results analysis

4.1 Microscopic analysis of sand particles

As predicted, the amount of particles and the velocity of particles in contact with the blade varied greatly with the angle of the blade upon the blade cutting into the sand. As was shown in Figure 8. Straight blade, 15° blade and 30°blade were analyzed. With the angle of the blade edge increased, the energy distribution of particles contacting with blades were different. From the statistical results in Table 4, the average velocity of the particles largely related to the shape of the blade.

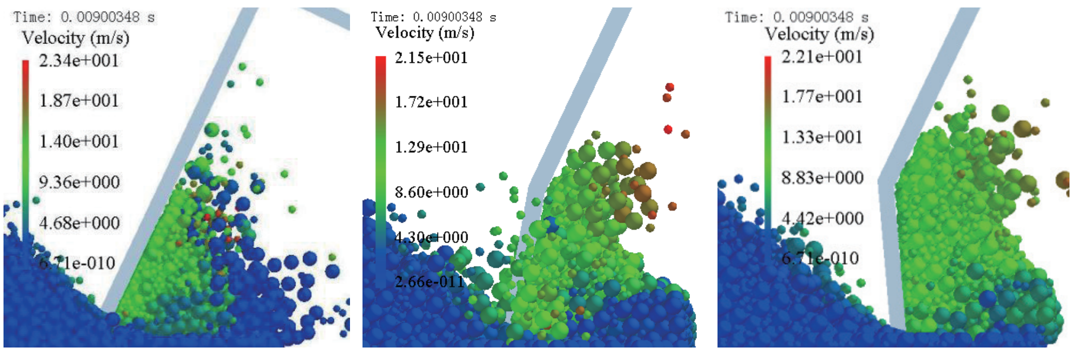
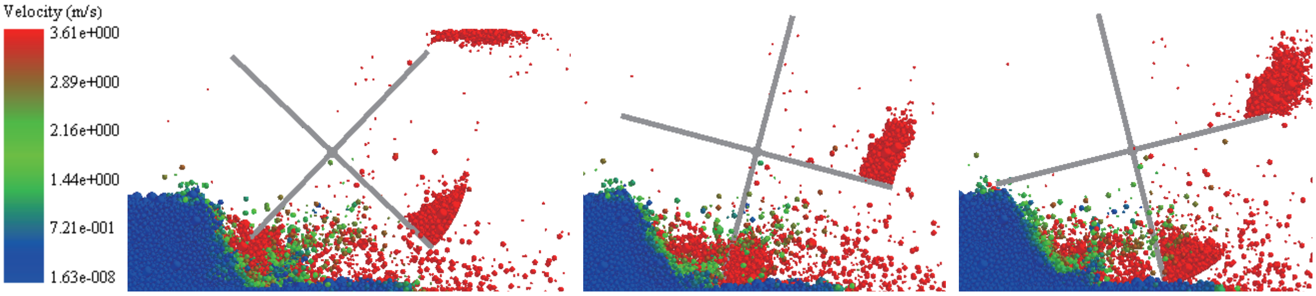


Figure 8. Speed map of sand particles upon straight, 15°and 30° blades cutting Sand

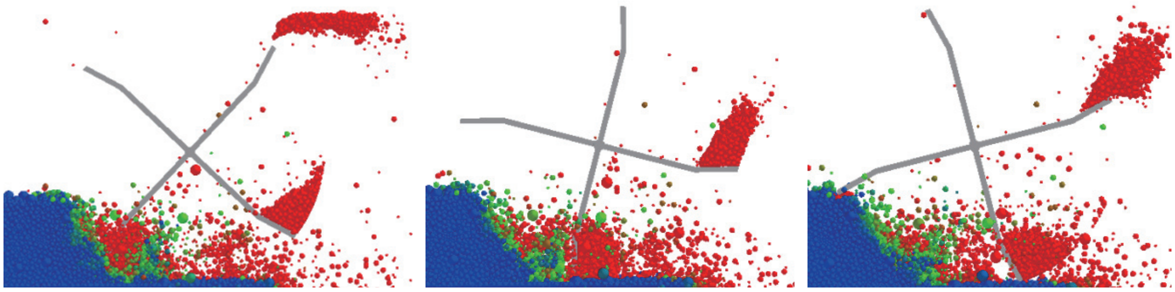
Table 4. Average velocity of the separated particles upon cutting occurred

Angle of the blade	Straight blade	15° blade	30° blade
Average particle velocity/（m/s)	7.53	8.32	8.43

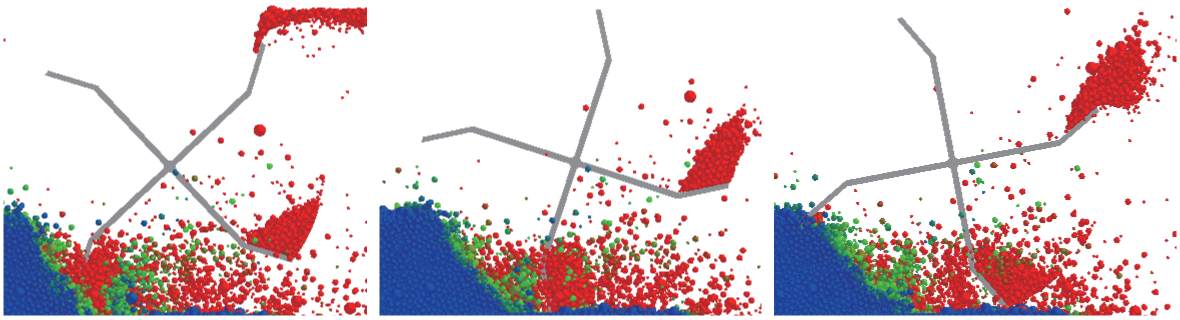
According to the analysis of the working conditions of sand shovel at different times during the sand collecting process, the velocity distribution of sand particles was closely related to the working angle of the sand shovel. Therefore, in order to analyze the overall force of the shovel, the observation of the movement state of the granules will help to further analyze the sand shovel and mechanism of sand interaction. Through the observation of several key moments in the sand collecting process, as shown in Figure 9, they pictures showed straight, 15° and 30 °blades in the process of cutting sand, penetration, separation moment. In those pictures, the change of the color means sand particles. The Fig10 indicated the velocity distribution of the sand particles at the moment of cutting, and the pictures can be used to analysis the law of blade angle and particle velocity distribution.



a. Incision, penetration and separation of straight blade on t=0.34s, 0.35s and 0.36s



b. Incision, penetration and separation of straight blade on t=0.34s, 0.35s and 0.36s



c. Incision, penetration and separation of straight blade on t=0.34s, 0.35s and 0.36s

Figure 9. Shape and particles velocity distribution during cutting process for different edge angle shovel

Totally, from the view of energy, an appropriate blade angle should be taken to keep the distribution of particle velocity uniformly and the efficiency of power effectively. Meanwhile, the impact of the blade can be decreased. So, a choice of a suitable angle for the shovel is very reasonable for optimizing the force of the sand shovel, microscopically.

4.2 Force analysis of the blades

At the same time, the torque of the sand collecting shovel was analyzed in a cycle of action. as shown in Figure 10. As the angle of the blade increased, the torque during the sand collection process declined significantly. However, the excessive edge angle of the blade may cause the sand collecting efficiency decreased. Therefore, experiments have shown that the edge angle should not be bigger than 30°.

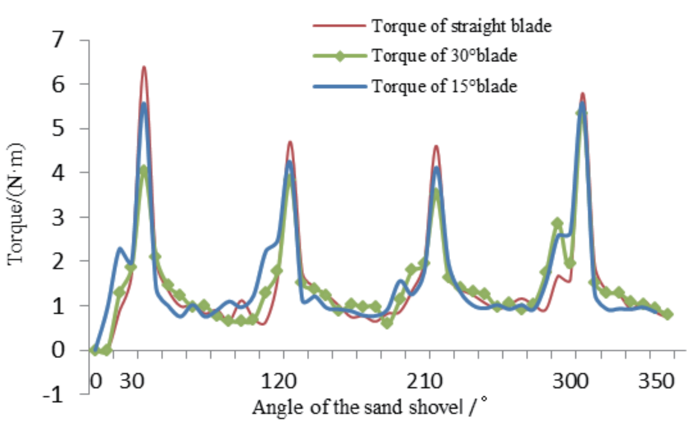
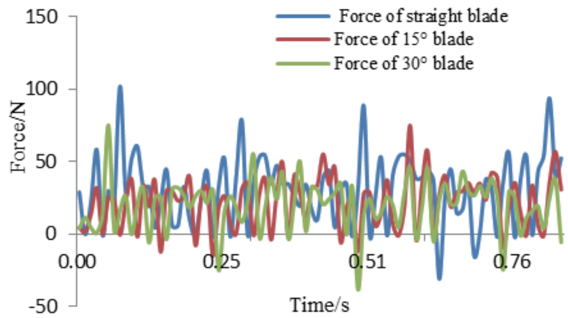


Figure 10. Simulation torque during sand shovel rotation at different angle

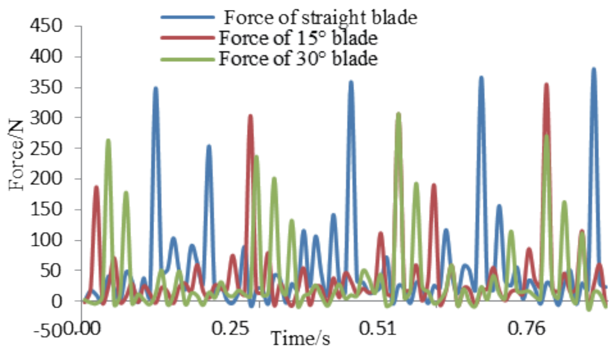
Comparing the data of Figure 10, it can be seen that the torque of the 30°blade worked in a better condition, meanwhile, the maximum torque declined 23.5% in one cycle, for straight blade and the 30°blade, which means the optimization was effective.

Although changing the edge angle of the blade can reduce the overall force of the blade, the reason for the force change cannot be clearly explained. In order to further analyze the mechanism of the change angle caused the force reduction, the three-direction force during the working process of the blade were analyzed, as is shown in Figure 11, the force in X, Y and

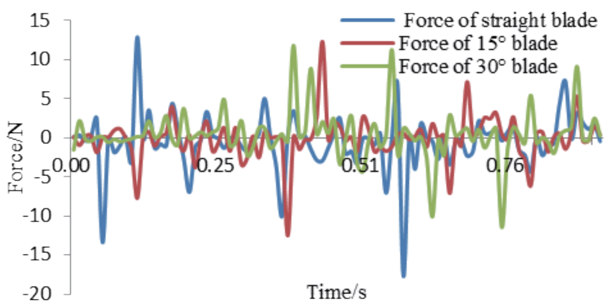
Z directions of the blade were analyzed, respectively.



a. Force of the X direction for three kinds of blades



b. Force of the Y direction for three kinds of blades



c. Force of the Z direction for three kinds of blades

Figure 11. Force of different sand shovels in X, Y and Z directions

According to the three-direction force analysis of the three kinds of shovels, it can be seen that with the angle of the sand shovel changed, the force trend varies with the degree showed a certain difference in three-direction, and a numerical analysis was performed, as is shown in Table 5.

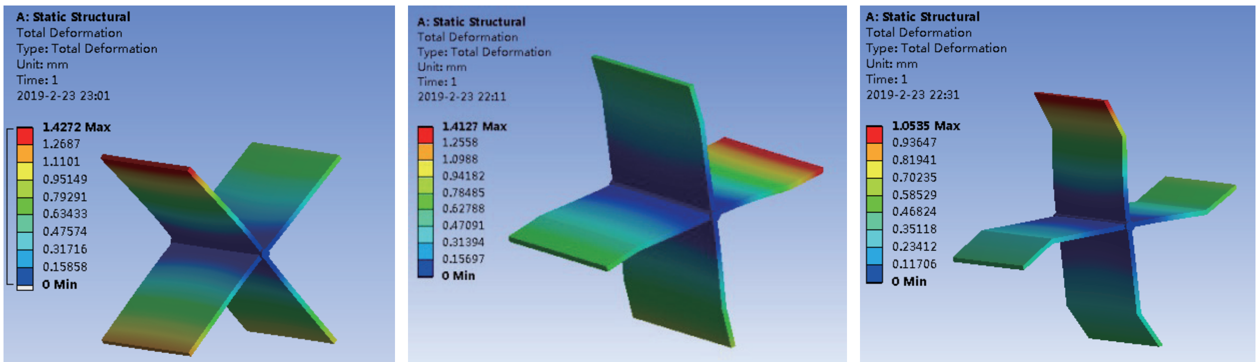
Table 5 Analysis of three-direction force values

	Direction	Straight blade	15°blade	30°blade
	X	30.79	21.92	19.54
Mean /N	Y	49.23	36.95	34.47
	Z	-0.51	-0.10	0.40
	X	102.04	74.95	75.15
Peak value/N	Y	380.30	355.08	306.8
	Z	12.84	12.28	11.77
	X	23.96	18.25	17.73
Standard deviation	Y	78.81	63.51	66.51
	Z	3.66	2.78	3.07

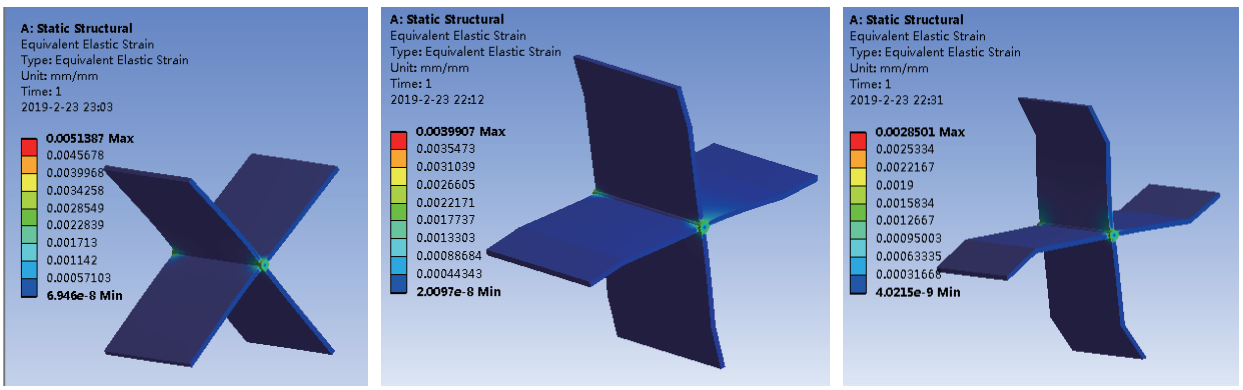
By comparing the force of the sand shovel in the three directions, the following results were obtained. Firstly, the increase of the blade angle is an effective way to reduce the impact of the sand shovel. The peak value, mean value and standard deviation of the shovel plates in three directions showed a decline in different degrees. Secondly, the X-direction force analysis shows that the sand cutting process is more stable when the angle of the blade increased; Thirdly, The standard deviation of the force regular shows a nonlinear variation with the increasing blade angle. Which means, different working conditions needs different blade angles which meets the applicable conditions.

4.3 Finite element analysis of the blade

In order to further analyze the force variation caused by the change of the edge angle, the data obtained by DEM were analyzed by finite element method (FEM). The mesh accuracy of the finite element model was 1 mm, the deformation and the stress of the blade analysis results were as Figure 12.



a. Deformation analysis of straight blade, 15°blade and 30°blade



b. Stress analysis of straight blade, 15°blade and 30°blade

Figure 12. Finite element analysis of the blade

Table 6. Finite element analysis of the blade

Angle of blade	Deformation /mm	Stress/mm
Straight blade	1.86	0.0049
15°blade	1.28	0.0034
30°blade	1.05	0.0028

It can be seen from the data in the table 6 that with an increase of the edge angle of the blade, the deformation and the stress of the blade decrease obviously. Therefore, the increase of the edge inclination of the spade plays an obvious role in improving the force of the shovel.

4.4 Force analysis of blade for different sand depth

In order to further explore the force of the shovel when the depth of the sand was different, the sand shovel model of 15° and 30°angle were further explored. When the sand collection depth was 50mm and 70mm respectively, the force of the blade were shown in Figure 13 and Figure 14.

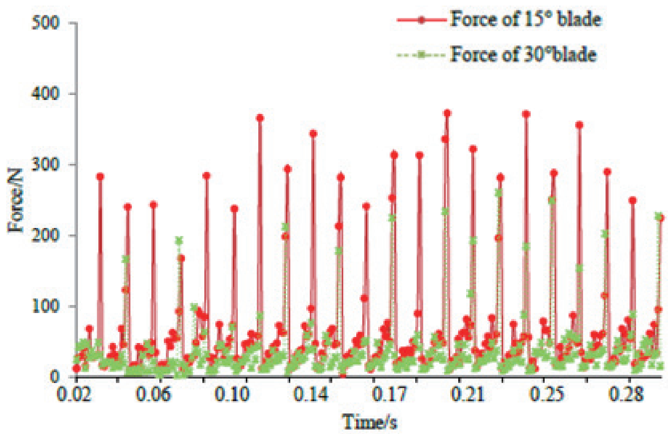


Figure 13. Force comparison chart of two kinds of blades when sand depth was 50mm

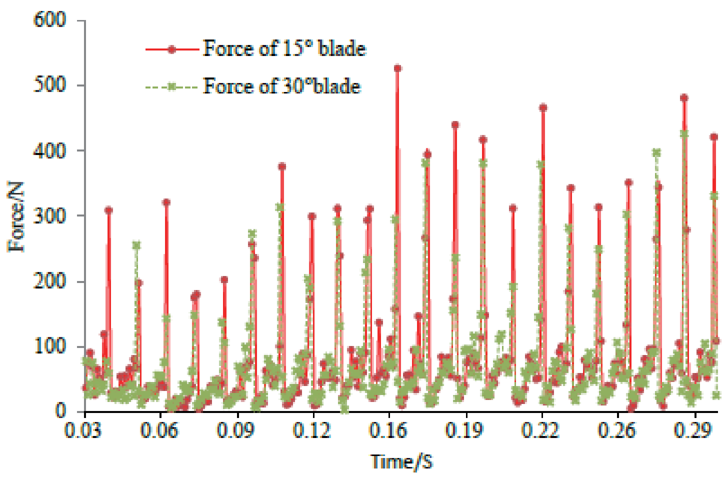


Figure 14. Force comparison chart of two kinds of blade when sand depth was 70mm

By comparison the 15° and 30° blades when the depth were 50mm and 70mm, respectively, it can be seen that with the depth increased, the force of the blade increased. When the depth of the sand shovel was 70mm, the force of the sand shovel is about 550N. However, the force improvement effect of the blade cutting sand was lower than that of the 30mm. According to the analysis, this may be caused by the depth of the cutting depth being greater than the length of the blade edge. At the same time, the sand collection depth was similar to the blade radius value (70:100), which also discount the advantage of the edge angle. However, the presence of the angle for the blade was still effective for the improvement on the force of the blade.

5. Conclusions

In this paper, the discrete element method is used to couple the multi-body dynamics method, and the force conditions of the 3 types of sand collecting shovels were analyzed, separately. The soil-sand collection test was carried out for the corresponding simulation model.

The force of the shovel was closely related to the velocity distribution of the sand particles. By changing the edge angle of the shovel, the force of the shovel can be changed, and the velocity distribution of the granules being changed was also different. The research results showed that change the edge angle of the shovels was an effective way to reduce the impact force .

The research results have certain reference significance for earthmoving machinery, agricultural machinery bulldozing and rotary tillage work.

Acknowledgements

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